METHOD AND APPARATUS FOR AUTOMATING A MATRIX-ASSISTED LASER DESORPTION/IONIZATION (MALDI) MASS SPECTROMETER

CROSS REFERENCE TO RELATED APPLICATIONS

This application is a continuation-in-part of application Ser. No. 09/507,423, filed February 18, 2000.

TECHNICAL FIELD OF THE INVENTION

The present invention relates generally to mass spectrometry and the analysis of chemical samples, and more particularly to the apparatuses and methods for the automated preparation and introduction of samples into a matrix-assisted laser desorption/ionization (MALDI) mass spectrometer. Described herein is a system utilizing a multiple part capillary device with a robot for use in mass spectrometry (particularly with ionization sources) to transport ions to the mass spectrometer for analysis therein.

BACKGROUND OF THE PRESENT INVENTION

The present invention relates to a means of delivering ions to a mass spectrometer. Mass spectrometry is an important tool in the analysis of a wide range of chemical compounds. Specifically, mass spectrometers can be used to determine the molecular weight of sample compounds. The analysis of samples by mass spectrometry consists of three main steps -- formation of ions from sample

material, mass analysis of the ions to separate the ions from one another according to ion mass, and detection of the ions. A variety of means exist in the field of mass spectrometry to perform each of these three functions. The particular combination of means used in a given spectrometer determine the characteristics of that spectrometer.

To mass analyze ions, for example, one might use a magnetic (B) or electrostatic (E) analyzer. Ions passing through a magnetic or electrostatic field will follow a curved path. In a magnetic field the curvature of the path will be indicative of the momentum-to-charge ratio of the ion. In an electrostatic field, the curvature of the path will be indicative of the energy-to-charge ratio of the ion. If magnetic and electrostatic analyzers are used consecutively, then both the momentum-to-charge and energy-to-charge ratios of the ions will be known and the mass of the ion will thereby be determined. Other mass analyzers are the quadrupole (Q), the ion cyclotron resonance (ICR), the time-of-flight (TOF), and the quadrupole ion trap analyzers.

Before mass analysis can begin, however, gas phase ions must be formed from sample material. If the sample material is sufficiently volatile, ions may be formed by electron ionization (EI) or chemical ionization (CI) of the gas phase sample molecules. For solid samples (e.g. semiconductors, or crystallized

materials), ions can be formed by desorption and ionization of sample molecules by bombardment with high energy particles. Secondary ion mass spectrometry (SIMS), for example, uses keV ions to desorb and ionize sample material. In the SIMS process a large amount of energy is deposited in the analyte molecules. As a result, fragile molecules will be fragmented. This fragmentation is undesirable in that information regarding the original composition of the sample -- e.g., the molecular weight of sample molecules -- will be impossible to determine.

For more labile, fragile molecules, other ionization methods now exist. The plasma desorption (PD) technique was introduced by Macfarlane et al. in 1974 (Macfarlane, R. D.; Skowronski, R. P.; Torgerson, D. F., *Biochem. Biophys. Res Commoun.* 60 (1974) 616). Macfarlane et al. discovered that the impact of high energy (MeV) ions on a surface, like SIMS would cause desorption and ionization of small analyte molecules, however, unlike SIMS, the PD process also results in the desorption of larger, more labile species -- e.g., insulin and other protein molecules.

Lasers have been used in a similar manner to induce desorption of biological or other labile molecules. See, for example, VanBreeman, R.B.: Snow, M.: Cotter, R.J., *Int. J. Mass Spectrom. Ion Phys.* 49 (1983) 35; Tabet, J.C.; Cotter, R.J., *Anal. Chem.* 56 (1984) 1662; or Olthoff, J.K.; Lys, I.: Demirev, P.: Cotter, R.

J., *Anal. Instrument.* 16 (1987) 93. Cotter et al. modified a CVC 2000 TOF mass spectrometer for infrared laser desorption of involatile biomolecules, using a Tachisto (Needham, Mass.) model 215G pulsed carbon dioxide laser. The plasma or laser desorption and ionization of labile molecules relies on the deposition of little or no energy in the analyte molecules of interest. The use of lasers to desorb and ionize labile molecules intact was enhanced by the introduction of matrix assisted laser desorption ionization (MALDI) (Tanaka, K.; Waki, H.; Ido, Y.; Akita, S.; Yoshida, Y.; Yoshica, T., *Rapid Commun. Mass Spectrom.* 2 (1988) 151 and Karas, M.; Hillenkamp, F., *Anal. Chem.* 60 (1988) 2299). In the MALDI process, an analyte is dissolved in a solid, organic matrix. Laser light having a wavelength that is absorbed by the solid matrix but not by the analyte is used to excite the sample. Thus, the matrix is excited directly by the laser, and the excited matrix sublimes into the gas phase carrying with it the analyte molecules. The analyte molecules are then ionized by proton, electron, or cation transfer from the matrix molecules to the analyte molecules. This process, MALDI, is typically used in conjunction with time-of-flight mass spectrometry (TOFMS) and can be used to measure the molecular weights of proteins in excess of 100,000 daltons.

Recently, MALDI has been especially gaining acceptance as a way to ionize large molecules such as proteins. MALDI requires

that samples applied to the surface of a sample support must be introduced into the vacuum system of the mass spectrometer. According to the prior art, a relatively large number of sample are introduced together on a support, and the sample support is moved within the vacuum system in such a way that the required sample is situated specifically in the focus of the laser's lens system. The analyte samples are placed on a sample support in the form of small drops of a solution, which dry very quickly and leave a sample spot suitable for MALDI. Normally a matrix substance is added to the solution for the MALDI process and the sample substances are encased in the crystals when the matrix substance crystallizes while drying. There are other methods known in the prior art, such as the application of sample substances to an already applied and dried matrix layer.

Current methods use visual control of the sample spots via microscopic observation. Thus, these are not truly automated. True automation opens up the possibility of processing large numbers of samples. It is well established within the art that microtiter plates are used for parallel processing of many samples. The body size of these plates is 80 by 125 millimeters, with a usable surface of 72 by 108 millimeters. There are commercially available sample processing systems which work with microtiter plates of this size. These originally contained 96 small

exchangeable reaction vials in a 9mm grid on a usable surface of 72 by 108 millimeters. Today, plates of the same size with 384 reaction wells imbedded solidly in plastic in a 4.5 mm grid have become standard.

The use of Atmospheric pressure ionization (API) is also well known in the prior art. Typically, analyte ions are produced from liquid solution at atmospheric pressure. One of the more widely used methods, known as electrospray ionization (ESI), was first suggested by Dole et al. (M. Dole, L.L. Mack, R.L. Hines, R.C. Mobley, L.D. Ferguson, M.B. Alice, *J. Chem. Phys.* 49, 2240, 1968). In the electrospray technique, analyte is dissolved in a liquid solution and sprayed from a needle. The spray is induced by the application of a potential difference between the needle (where the liquid emerges) and a counter electrode. By subjecting the sample liquid to a strong electric field, it becomes charged, and as a result, it "breaks up" into smaller particles if the charge imposed on the liquid's surface is strong enough to overcome the surface tension of the liquid (i.e., as the particles attempt to disperse the charge and return to a lower energy state). This results in the formation of finely charged droplets of solution containing analyte molecules. These droplets further evaporate leaving behind bare charged analyte ions.

Electrospray mass spectrometry (ESMS) was introduced by

Yamashita and Fein (M. Yamashita and M.B. Fein, *J. Phys. Chem.* 88, 4671, 1984). To establish this combination of ESI and MS, ions had to be formed at atmospheric pressure, then introduced into the vacuum system of a mass analyzer via a differentially pumped interface. The combination of ESI and MS affords scientists the opportunity to mass analyze a wide range of samples, and ESMS is now widely used primarily in the analysis of biomolecules (e.g. proteins) and complex organic molecules.

In the intervening years a number of means and methods useful to ESMS and API-MS have been developed. Specifically, a great deal of work has focused on sprayers and ionization chambers. In addition to the original electrospray technique, pneumatic assisted electrospray, dual electrospray, and nano electrospray are now also widely available. Pneumatic assisted electrospray (A.P. Bruins, T.R. Covey, and J.D. Henion, Anal. Chem. 59, 2642, 1987) uses nebulizing gas flowing past the tip of the spray needle to assist in the formation of droplets. The nebulization gas assists in the formation of the spray and thereby makes the operation of ESI easier. Nano electrospray (M.S. Wilm, M. Mann, *Int. J. Mass Spectrom. Ion Processes* 136, 167, 1994) employs a much smaller diameter needle than the original electrospray. As a result the flow rate of sample to the tip is lower and the droplets in the spray are finer. However, the ion signal provided by nano

electrospray in conjunction with MS is essentially the same as with the original electrospray. Nano electrospray is therefore much more sensitive with respect to the amount of material necessary to perform a given analysis.

Sample preparation robots (e.g. Gilson) have been used in the prior art for the automated injection of sample aliquots into an ESI source. In such a case, solution is pumped continuously from a resevoir to the sprayer of an ESI source. Sampe aliquots are injected into this solution stream and are thereby carried through a transfer line to the sprayer.

Many other ion production methods might be used at atmospheric or elevated pressure. For example, MALDI has recently been adapted by Victor Laiko and Alma Burlingame to work at atmospheric pressure (Atmospheric Pressure Matrix Assisted Laser Desorption Ionization, poster #1121, 4th International Symposium on Mass Spectrometry in the Health and Life Sciences, San Francisco, Aug. 25 - 29, 1998) and by Standing et al. at elevated pressures (Time of Flight Mass Spectrometry of Biomolecules with Orthogonal Injection + Collisional Cooling, poster #1272, 4th International Symposium on Mass Spectrometry in the Health and Life Sciences, San Francisco, Aug. 25 - 29, 1998; and Orthogonal Injection TOFMS *Anal. Chem.* 71(13), 452A (1999)). The benefit of adapting ion sources in this manner is that the ion optics and mass spectral results are largely

independent of the ion production method used.

An elevated pressure ion source always has an ion production region (where ions are produced) and an ion transfer region (where ions are transferred through differential pumping stages and into the mass analyzer). The ion production region is at an elevated pressure -- most often atmospheric pressure -- with respect to the analyzer.

In much of the prior art the ion production region will often include an ionization "chamber". In an ESI source, for example, liquid samples are "sprayed" into the "chamber" to form ions. The design of the ionization chamber used in conjunction with API-MS has had a significant impact on the availability and use of these ionization methods with MS. Prior art ionization chambers are inflexible in that a given ionization chamber can be used readily with only a single ionization method and a fixed configuration of sprayers. For example, in order to change from a simple electrospray method to a nano electrospray method of ionization, one had to remove the electrospray ionization chamber from the source and replace it with a nano electrospray chamber (see also, Gourley et al. United States Pat. No. 5,753,910, entitled Angled Chamber Seal for Atmospheric Pressure Ionization Mass Spectrometry). In a co-pending application entitled Ionization Chamber For Atmospheric Pressure Ionization, this problem is

addressed by disclosing an API ionization chamber providing multiple ports for employing multiple devices in a variety of combinations (e.g., any type of sprayer, lamp, microscope, camera or other such device in various combinations). Further, any given sprayer may produce ions in a manner that is synchronous or asynchronous with the spray from any or all of the other sprayers. By spraying in an asynchronous manner, analyte from a multitude of inlets may be sampled in a multiplexed manner.

Analyte ions produced via an API method need to be transported from the ionization region through regions of differing pressures and ultimately to a mass analyzer for subsequent analysis (e.g., via TOFMS, Fourier transform mass spectrometry (FTMS), etc.). In prior art sources, this was accomplished through use of a small orifice or capillary tube between the ionization region and the vacuum region. An example of such a prior art capillary tube is shown in FIG. 1. As depicted, capillary 7 comprises a generally cylindrical glass tube 2 having an internal bore 4. The ends of capillary 7 include a metal coating (e.g., platinum, copper, etc.) to form conductors 5 which encompass the outer surface of capillary 7 at its ends, leaving a central aperture 6 such that the entrance and exit to internal bore 3 are left uncovered. Conductors 5 may be connected to electrical contacts (not shown) in order to maintain a desired space potential at each end of capillary 7. In

operation, a first electrode (one of conductors 5) of capillary 7 may be maintained at an extreme negative potential (e.g., -4,500V), while the other electrode (the other of conductors 5), which may form the first stage of a multi-stage lensing system for the final direction of the ions to the spectrometer, may be maintained at a positive potential (e.g., 160 volts).

It is often observed that the capillaries used in MS analysis acquire deposits over time. Therefore, through normal operation the capillaries need to be regularly cleaned or even replaced. To do so, the MS system must be turned off before the capillary can be removed -- requiring the pumps to be shut down and the vacuum system to be broken -- thereby rendering the system unavailable for hours and even days at a time.

More recently, Lee et al. U.S. Pat. No. 5,965,883 attempted to solve this problem in the manner shown by FIG. 2. Shown in FIG. 2 is capillary 8 which comprises an outer capillary sleeve 9 surrounding an inner capillary tube 10. Sleeve 9 has substantially cylindrical inner surface 11 and outer surface 14. Similarly, tube 10 has substantially cylindrical inner surface 12 and outer surface 13. The innermost channel, or bore, of capillary 8 is substantially formed by inner surface 12 of tube 10. Capillary 8 is substantially radially symmetrical about its central longitudinal axis 15 extending from an upstream end 16 to a

downstream end 17. At each end, capillary 8 has conductive end caps 18 comprising the unitary combination of a tubular body having cylindrical inner surface 20 and outer surface 21 and an end plate 22 having inner surface 23 and outer surface 24 with a central aperture. The tubular body of end cap 18 encompasses and is in circumferential engagement with a reduced diameter portion 25 of sleeve 9 adjacent to the respective ends of capillary 8, such that the external diameter of end cap 18 is substantially the same as the external diameter of sleeve outer surface 14.

In order to remove tube 10, end cap 18 at the upstream end of capillary 8 is first removed. A removal tool (not shown) is inserted into the tube as to engage the tube's inner surface 12. It is further suggested by the prior art that in order to remove tube 10 it may be necessary to apply a slight torque orthogonal to axis 15, or other appropriate means such as bonding a removal tool to the tube using an adhesive. Once the tube is withdrawn, a replacement tube may be inserted into sleeve 9. However, this too is difficult and cumbersome, requiring tools to remove and replace the inner capillary tube.

Such prior art designs for the transfer capillary have inherent limitations relating to geometry, orientation, and ease of use. The capillary according to these prior art designs is substantially fixed in the source. Only if the instrument -- or at

least the source -- is vented to atmospheric pressure can the capillary be removed. The geometric relation of the capillary is therefore fixed with respect to the source and all its components. This implies that the ion production means - e.g. an electrospray needle, atmospheric pressure chemical ionization sprayer, or MALDI probe - must be positioned with respect to the capillary entrance. In order to change from one ion production means to another - e.g. from an electrospray needle to a nano electrospray needle - the first means must be removed from the vicinity of the capillary entrance and the second must then be properly positioned with respect to the capillary entrance. For any production means, there will be an optimum geometry between the means and the capillary entrance at which the ion current passing into the analyzer is maximized. To achieve this optimum, a positioning means must be provided for positioning the ion production means with respect to the capillary entrance. This might take the form of precision machined components, a translation stage on which the ion production means is mounted, or some other device. If the ion production means is required or desired to be remote from the source, a long, fixed length capillary would have to be produced and installed (in a fixed position) in the source.

Another limitation of prior art capillaries relates to the orientation of the capillary bore with respect to the ion

production means. Such orientation can be important for the operation of the source. One major consideration in the operation of an electrospray source is the formation of large droplets from the analyte solution at the spray needle. Such droplets do not readily evaporate. If these droplets enter the capillary, they may cause the capillary to become contaminated with a residue of analyte molecules and salts. In view of this, Apfel et al. in US patents 5,495,108 and 5,750,988 describe apparatuses for API sources wherein the axis of the bore of the capillary 110 is at an angle of 90° with respect the axis of the bore of the spray needle 111, as depicted in FIG. 3. According to Apfel et al., certain experimental conditions lead to the production of large droplets by the spray needle. These large droplets will move away from the spray needle along the axis of the sprayer. However, an electric field between the spray needle and the capillary will cause ions formed from the spray to move towards the capillary. In this way, the ions are separated from the spray droplets and the droplets do not enter the capillary. However, this orientation is fixed in the prior art source of Apfel. To change this orientation, one would have to move the spray needle.

Prior art capillaries are further limited in the geometry of the capillary bore. That is, prior art capillaries, as depicted in FIGs. 1-3, are substantially straight (i.e., cylindrically

symmetric) and fixed (i.e., the geometry of the capillary and its bore is fixed at the time of manufacture). However, as described in the co-pending application METHOD AND APPARATUS FOR A MULTIPLE PART CAPILLARY DEVICE FOR USE IN MASS SPECTROMETRY Serial No. 09/507,423 a capillary which can be cleaned or replaced without the need to shut down the entire mass spectrometer in which it resides now exists. The use of this capillary within the system described herein allows ionization to occur within the MALDI tray as opposed to occurring within the vacuum.

Others have disclosed atmospheric pressure matrix-assisted laser desoprtion/ionization (AP-MALDI). Laiko et al. disclose an AP-MALDI apparatus for the transfer of ions from an atmospheric pressure ionization region to a high vacuum region, which is pneumatically assisted (PA) by a stream of nitrogen gas. (Victor V. Laiko, Michael A. Baldwin and Alma L. Burlingame, "Atmospheric Pressure Matrix-Assisted Laser Desorption/Ionization Mass Spectrometry", Analytical Chemistry, Vol. 72, No. 4, February 4, 2000). The invention of matrix-assisted laser desoprtion/ionization (MALDI) and electrospray ionization (ESI) are considered the most powerful tools for detection, identification, and characterization of biopolymers such as peptides, proteins, and DNA. MALDI and ESI enable the production of intact heavy molecular ions from a condensed phase, where MALDI is for solids and ESI is

for liquids. Although, MALDI's target material density drops rapidly after laser desorption, from a high value characteristic of the initial solid phase to a very low value. Hence, a new ionization source combines atmospheric pressure and MALDI, which was called atmospheric pressure (AP) MALDI. AP-MALDI produces a uniform ion cloud under atmospheric pressure conditions. The apparatus disclosed in Laiko, i.e., for PA-AP-MALDI, is readily interchangeable with electrospray ionization on an orthoganal acceleration TOF mass spectrometer. According to Laiko, PA-AP-MALDI can detect low femtomole amounts of peptides in mixtures with good signal-to-noise ratio and with less discrimination for the detection of individual peptides in a protein digest. Thus, total sample consumption is higher for PA-AP-MALDI than vacuum MALDI, as the transfer of ions into the vacuum system is relatively inefficient.

Yet another high throughput MALDI elevated pressure mass spectrometry technique and apparatus is disclosed by Schevchenko et al. ("MALDI Quadrupole Time-of-Flight Mass Spectrometry: A Powerful Tool for Proteomic Research", Analytical Chemistry, Vol. 72, No. 9, May 1, 2000). More particularly, Shevchenko et al. disclose use of a MALDI QqTOF mass spectrometer to achieve high mass resolution and accuracy in the identification of proteins. The apparatus disclosed by Schevchenko includes interfacing an orthogonal

injection TOF MS to a hybrid quadrupole TOF MS (QqTOF) to form a MALDI QqTOF instrument, whereby a collisional damping interface cools the ions before they enter the analytical quadrupole Q. According to Schevchenko, once the ions are cooled, they can be transported through the quadrupoles more efficiently for measurement of the whole mass spectrum. A precursor ion can be selected in the quadrupole Q and fragmented in the collision cell q. Measurement of the product ions in the TOF section then provides a MS/MS spectrum of the selected precursor, thus carrying out both peptide mass mapping and MS/MS measurement on the same target in the same experiment. This process provides a high mass selection of precursor ions, precise tuning of the collision energy, and a much simplified calibration procedure. Also, Schevchenko et al. suggest that such an analytical approach lends itself to automation in obtaining MALDI spectra. However, Schevchenko et al. are silent as to how this might be achieved.

Also, Franzen et al. U.S. Patent No. 5,663,561 (Franzen) teaches a device and method for the desorption and ionization of labile substance molecules at atmospheric pressure by MALD followed by chemical ionization (APCI). The method of Franzen consists of desorbing the analyte substances, which are mixed with decomposable substances (matrix substances) in solid form on a solid support, by laser irradiation at atmospheric pressure into a gas stream, and to

add sufficient ions for proton transfer reactions to the gas stream. The objective of the method and apparatus of Franzen et al. is to transfer large molecules on solid sample support from solid state to a state of ionized gas phase molecules to be subjected to mass spectrometric analysis in an efficient manner.

The system disclosed in Franzen et al. generates ions from macromolecular substances in an area outside the vacuum, instead of within the vacuum, and separates the ionization process from the desorption process. Since new development of ion transfer from atmospheric pressure have become possible, external ionization has become effective and relatively economical. Thus, Franzen et al. recognized the problem of evaporating the non-volatile analyte substances into the surrounding gas. Therefore, the method and apparatus of Franzen et al. support the desorption process by photolytic and thermolytic processes triggered by laser photons. Consequently, the matrix material would decompose explosion-like into small gas molecules which can blast the analyte molecules into the surrounding gas. Then, the matrix molecules in the photolytic and thermolytic processes are broken down into smaller molecules. According to Franzen et al., if a matrix substance is selected in such a way that the product of its decomposition is gaseous in its normal state, the large, embedded analyte molecules would be catapulted into the gas phase. Of course, the matrix material then has to be selected such that the transfer of heat to the analyte molecules is minimal.

Moreover, in each of these systems, the samples are positioned outside of the vacuum system of the mass spectrometer for ionization (e.g., a MALDI target, sample plate, etc.). The present invention recognizes this and provides a simple and efficient method and apparatus for ionizing samples and introducing the sample ions into a mass spectrometer with the sample positioned outside of the vacuum system of the mass spectrometer.

Also, it has been recognized that a need exists for a simple, fast, efficient and reliable means of integrating a robot with various ionization sources for automating the preparation and introduction of samples into a mass spectrometer, and more particularly into an atmospheric pressure MALDI mass spectrometer. The present invention provides a novel solution to this problem.

SUMMARY OF THE INVENTION

The present invention relates generally to mass spectrometry and the analysis of chemical samples, and more particularly to the robotic interface of sample introduction into a source region of a mass spectrometer using specially designed multiple part capillary tubes.

It is a first object of the invention to provide an improved method and apparatus for the automatic preparation and introduction of samples into a mass spectrometer for subsequent mass analysis.

It is another object of the invention to provide a method and apparatus for the automatic preparation and introduction of samples

maintained at atmospheric pressure (i.e., outside the vacuum system) into a mass spectrometer for subsequent mass analysis.

It is yet another object of the invention to provide a method and apparatus whereby a single robot is used for the automatic preparation and introduction of samples into a mass spectrometer for subsequent mass analysis.

It is still a further object of the invention to provide a method and apparatus for the automatic preparation and introduction of samples into a mass spectrometer from a plurality of electrospray ionization (ESI) sprayers for subsequent mass analysis.

Yet another aspect of the present invention is to provide a capillary for use in an ion source having improved flexibility and accessibility over prior art designs. A capillary according to the invention consists of at least two sections joined together end to end such that gas and sample material in the gas can be transmitted through the capillary across a pressure differential. The capillary is intended for use in an ion source wherein ions are produced at an elevated pressure and transported by the capillary into a vacuum region of the source.

Still another object of the invention is to allow for the removal of one or more sections of the capillary (for cleaning or replacement) without having to shut down the pumping system of the instrument to which it is attached. These sections may be made of different materials -- e.g., glass, metal, composite, etc. -- which

may be either electrically conducting or non-conducting. Also, each section of the capillary according to the invention does not have to be straight or rigid, rather, one or more of the sections may be flexible such that it (or they) can bend in any direction.

Another object of the invention is to utilize a multiple part capillary which offers improved flexibility in its geometric orientation with respect to other devices in the ionization source -- especially the ion production means. For example, the axis of the bore or "channel" of the capillary at the capillary entrance might be positioned at any angle with respect to the ion production means. This angle, as discussed in Apfel U.S. Patent Nos. 5,495,108 and 5,750,988 can be important, for example, in the separation of spray droplets from desolvated analyte ions. Also according to the present invention, the entrance section of the capillary might be modified or exchanged before or during instrument operation to effect a change in the orientation of the entrance with respect to the ion production means or other device.

This flexibility applies to the translational position of the entrance of the capillary as well as its angular orientation. That is, the position of the entrance of the capillary might be changed before or during instrument operation by either modification or exchange of the first section of the capillary. This allows for the transmission of ions from a variety of locations either near or removed from the immediate location of the source.

Still another object of the present invention is to utilize a

multipurpose multiple part capillary wherein the bore or "channel" of one or more of the sections of the multiple part capillary may comprise any useful geometry (i.e., straight, helical, wave-like, etc.). For instance, it may be particularly useful to have an inner channel of helical geometry. This will cause larger particles (e.g., droplets from electrospray) to collide with the walls of the capillary, while allowing smaller particles (e.g., fully desolvated electrosprayed ions) to pass through the capillary. Note that the geometry of the bore may be, but is not necessarily, related to the outer surface of the capillary. That is, a capillary might have a cylindrically symmetric outer surface but have an inner bore which is helical.

Yet another purpose of the present invention is to provide a simple and efficient method and apparatus for integrating multiple source assemblies. A complete ion source may include a multitude of sub-assemblies. For example, an ion source might include an ion production means sub-assembly and vacuum sub-assembly. The ion production means sub-assembly might include a spray needle, its holder, a translation stage, etc. The vacuum sub-assembly might contain pumps, pumping restrictions, and ion optics for guiding ions into the mass analyzer. In prior art ion sources and MS instruments, the capillary would conventionally be integrated entirely in one sub-assembly -- the vacuum sub-assembly. As a result, significant effort is required in prior art systems to align the ion production means sub-assembly -- specifically the

spray needle -- with the vacuum sub-assembly -- specifically the capillary entrance. The multiple part capillary according to the present invention eases the integration of such sub-assemblies by including capillary sections in each of the sub-assembly. The sub-assemblies are integrated by joining the capillary sections together. Any necessary alignments are performed within a given sub-assembly -- e.g. alignment of the spray needle with the first section of capillary. This sub-assembly arrangement allows for the automation of a MALDI-TOF mass spectrometer.

It is a further purpose of the present invention to provide flexibility when using a particular mass spectrometer by providing efficient use of a plurality of ionization sources. For example, in combination with the ionization chamber described in co-pending application serial no. 09/263,659, entitled IONIZATION CHAMBER FOR ATMOSPHERIC PRESSURE IONIZATION MASS SPECTROMETRY, which is incorporated herein by reference, the present invention provides added flexibility for switching from one ionization source to another or from one sample to another. Specifically, the capillary according to the invention is capable of efficiently and accurately being used with multiple electrospray sources. In addition, the capillary according to the invention is useful in multiplexing.

Another purpose of the invention is to provide a multiple part capillary which can be used with chromatographic sample preparation (e.g., liquid chromatography, capillary electrophoresis, etc.). The effluent from such a chromatographic column may be injected

directly or indirectly into one of the sprayers. A plurality of such chromatographic columns may be used in conjunction with a plurality of sprayers -- for example one sprayer per column. The presence of analyte in the effluent of any given column might be detected by any appropriate mans, for example a UV detector. When analyte is detected in this way, the sprayer associated with the column in question is "turned on" so that while analyte is present the sprayer is producing ions but otherwise the sprayer does not. If analyte is present simultaneously at more than one sprayer, the sprayers are multiplexed, as discussed above.

It is yet another purpose of the invention to allow a simple, fast, efficient and reliable means of integrating a robot with various ionization sources and techniques. The multiple part capillary disclosed herein allows such a means for integrating a robot with any of a variety of ionization sources, including elevated pressure and atmospheric pressure sources. The design of the multiple part capillary according to the present invention provides added versatility to the use of ionization chambers as well as to the use and performance of any new and existing ionization methods.

Further, the present system allows for the removal of one or more sections of the capillary (for cleaning or replacement) without having to shut down the pumping system or the instrument to which it is attached. The capillary according to the present invention can, among other things, be made from different

materials, take on different sizes, shapes or forms, as well as perform different functions. Furthermore, to provide a fully automated system for the analysis of a variety of chemical species efficiently and cost effectively.

Other objects, features, and characteristics of the present invention, as well as the methods of operation and functions of the related elements of the structure, and the combination of parts and economies of manufacture, will become more apparent upon consideration of the following detailed description with reference to the accompanying drawings, all of which form a part of this specification.

BRIEF DESCRIPTION OF THE DRAWINGS

A further understanding of the present invention can be obtained by reference to a preferred embodiment set forth in the illustrations of the accompanying drawings. Although the illustrated embodiment is merely exemplary of systems for carrying out the present invention, both the organization and method of operation of the invention, in general, together with further objectives and advantages thereof, may be more easily understood by reference to the drawings and the following description. The drawings are not intended to limit the scope of this invention, which is set forth with particularity in the claims as appended or as subsequently amended, but merely to clarify and exemplify the invention.

For a more complete understanding of the present invention, reference is now made to the following drawings in which:

FIG. 1 shows a partial cut-away cross-sectional view of a prior art capillary comprising a unitary glass tube having a cylindrical outer surface and internal bore;

FIG. 2 shows a partial cut-away cross sectional view of another prior art capillary comprising a concentric outer capillary sleeve and inner capillary tube;

FIG. 3 shows a prior art spray chamber of a prior art electrospray ionization source wherein the channel of the spray needle is oriented orthogonal to the channel of the capillary;

FIG. 4 shows a preferred embodiment of a multiple part capillary according to the present invention;

FIG. 5 shows an alternate embodiment of the multiple part capillary, wherein the channel of the first section comprises a helical structure;

FIG. 6 shows an ESI sprayer needle oriented at an angle θ with respect to the inlet to the channel and an angle α with respect to the body of an embodiment of the multiple part capillary according to the present invention;

FIG. 7 shows an embodiment of the multiple part capillary according to the present invention as used with an ESI ionization source;

FIG. 8 shows a multiple part capillary according to the present invention as a means for integrating two source sub-

assemblies;

FIG. 9 shows the multiple part capillary according to the present invention as a means for integrating a sample preparation robot with an API source for mass spectrometry;

FIG. 10 shows an embodiment of the multiple part capillary according to the present invention as a means for integrating a sample preparation robot with an elevated pressure MALDI source for mass spectrometry; and

FIG. 11 shows a close-up view of the use of the multiple part capillary with a MALDI probe in accordance with the present invention.

DETAILED DESCRIPTION OF A PREFERRED EMBODIMENT

As required, a detailed illustrative embodiment of the present invention is disclosed herein. However, techniques, systems and operating structures in accordance with the present invention may be embodied in a wide variety of sizes, shaped, forms and modes, some of which may be quite different from those in the disclosed embodiment. Consequently, the specific structural and functional details disclosed herein are merely representative, yet in that regard, they are deemed to afford the best embodiment for purposes of disclosure and to provide a basis for the claims herein which define the scope of the present invention.

The following presents a detailed description of a preferred

embodiment of the present invention, as well as some alternate embodiments of the invention. As discussed above, the present invention relates generally to the mass spectroscopic analysis of chemical samples and more particularly to mass spectrometry. Specifically, an apparatus and method are described for transport of ions to the mass spectrometer. Reference is herein made to the figures, wherein the numerals representing particular parts are consistently used throughout the figures and accompanying discussion.

With reference first to FIG. 4, shown is multiple part capillary 35 according to a preferred embodiment of the present invention. As depicted in FIG. 4, multiple part capillary 35 comprises: first section 28 having capillary inlet end 26 and first channel 27; union 29 having o-ring 31; second section 33 having second channel 32 and capillary outlet end 34; and metal coatings 30A and 30B. According to the preferred embodiment, first section 28 is connected to second section 33 by union 29. In the preferred embodiment, union 29 is substantially cylindrical having two coaxial bores, 60 and 61, and through hole 62 of the same diameter as channels 26 and 32. In the preferred embodiment, section 28 and union 29 are composed of metal - e.g. stainless steel. The inner diameter of bore 60 and the outer diameter of section 28 are chosen to achieve a "press fit" when section 28 is inserted into bore 60. Because the press fit is designed to be tight, union 29 is thereby strongly affixed to

section 28 and a gas seal is produced between union 29 and section 28 at the surface of the bore. The inner diameter of bore 61 is of slightly larger diameter than the outer diameter of section 33 (including metal coating 30A) so as to produce a "slip fit" between union 29 and section 33. A gas seal is established between bore 61 and section 33 via o-ring 31. Electrical contact between metal coating 30A, union 29, and section 28 via direct physical contact between the three. Through hole 62 allows for the transmission of gas from entrance end 26 through to exit end 34 of the capillary. Ideally, union 29 and sections 28 and 33 are formed in such a way as to eliminate any "dead volume" between these components. To accomplish this, the ends of sections 28 and 33 are formed to be flush with the inner surface of union 29. Note that the body of section 33 - excluding metal coatings 30A and 30B - is composed of glass in the preferred embodiment. As a result, metal coating 30A - together with union 29 and section 28 - can be maintained at a different electrical potential than metal coating 30B.

Alternatively, union 29, and sections 28 and 33 may be composed of a variety of materials conducting or non-conducting; the outer diameters of the sections may differ substantially from one another; the inner diameters of the sections may differ substantially from one another; either or both ends or any or all sections may be covered with a metal or other coating; rather than a coating, the ends or capillary sections may be covered

with a cap composed of metal or other material; the capillary may be composed of more than two sections always with one fewer union than sections; and the union may be any means for removably securing the sections of capillary together and providing an airtight seal between these sections.

Each end of union 29 could comprise a generally cylindrical opening having an internal diameter slightly larger than the external diameter of the end of the capillary section which is to be inserted therein. In such an embodiment, a gas seal is made with each capillary section via an o-ring similar to o-ring 31. As a further alternative, one might use springs to accomplish electrical contact between union 29 and sections 28 and 33. In this case a conducting spring would be positioned in union 29 adjacent to o-ring 31.

Moreover, in a preferred embodiment of the capillary according to the invention, the length of first section 28 is less than (even substantially less than) the length of second section 33. More specifically, the dimensions of first section 28 and second section 33 are such that within a range of desired pressure differentials across capillary 35, a gas flow rate within a desired range will be achieved. For example, the length of second section 33 and the internal diameter of second channel 32 are such that the gas transport across second section 33 alone (i.e., with first section 28 removed) at the desired pressure differential will not overload the pumps which generate the

vacuum in the source chamber of the system. This allows the removal (e.g., for cleaning or replacement) of first section 28 of capillary 35 without shutting down the pumping system of the mass spectrometer.

While the prior art, as depicted in FIG. 2, attempts to accomplish removal, without shutting down the vacuum, it is difficult and cumbersome. As discussed previously, tools and adhesives may be required to remove and replace the capillary. The multiple part capillary according to the present invention provides a much simpler method and apparatus for accomplishing this result (i.e., without the use of adhesives, tools, etc.).

Turning next to FIG. 5, an alternate embodiment of capillary 35 is shown wherein capillary section 28 has a serpentine internal channel 64. That is, the geometric structure of the internal channel of the capillary section is sinusoidal. Of course, other geometrical structures (i.e., helical, varying diameter, non-uniform, etc.) may be used in accordance with the invention. Having sinusoidal internal channel 64 causes larger particles -- such as droplets from an electrospray -- to collide with the walls of the channel and thereby not pass completely through the capillary. On the other hand, smaller particles -- such as fully desolvated electrosprayed ions -- do not collide with the walls and pass completely through the capillary. The curved (or sinusoidal) geometry of channel 64 also increases the length of the channel, which provides the advantage of permitting

a larger diameter channel. Such a larger diameter channel may be advantageous in that it may provide greater acceptance of sampled species (e.g., electrosprayed ions, etc.) at a given flow rate and pressure differential. Alternatively, a sinusoidal -- or any other geometry -- channel may be used in either first section 28 or second section 33, or both.

In accordance with the present invention, it is observed that the introduction of ions from an ionization means into the multiple part capillary of the invention may be accomplished at any angle of incidence between the ionization means and the inlet of the capillary. Referring now to FIG. 6, shown is an embodiment of the multiple part capillary according to the invention as used with an ESI sprayer 65 wherein axis 70 of sprayer 65 is oriented at angle α 66 with respect to axis 69 of the body of capillary 72. However, because channel 73 of capillary section 74 is curved, angle θ 67 between sprayer axis 70 and axis 71 of channel entrance 68 can be substantially different than angle α 66. The embodiment shown in FIG. 6 demonstrates that the capillary entrance angle α 66 may be any angle from 0° and 180°. The specific angle selected is dependent upon, among other things, the sample species being tested, the ionization source used, etc. As discussed above, the electrospray process results in the formation of charged droplets and molecular ions. The presence of large droplets in the spray can result in contamination of the capillary and generally poor

instrument performance. One way of limiting the influence of large droplets on instrument performance is to spray away from the capillary entrance. That is, the spray needle is oriented so that it is not pointed directly at the capillary entrance. Large droplets formed in a source with such a geometry will tend to move along the axis of the spray needle and not enter the capillary, whereas desolvated ions will be attracted to the capillary entrance by the electrostatic field between the spray needle and the capillary. Thus, in the embodiment of figure 6, smaller angles α 66 and θ 67 will tend to reduce the fraction of droplets that enter the capillary.

In any case, the sinusoidal geometry of channel 73 tends to limit the contamination of capillary 72 due to large droplets into section 74. Large droplets which enter the capillary will tend to strike the walls of channel 73 and not pass through to section 33. Section 74 can be removed from the system - by pulling it off along axis 69 - and cleaned without necessarily shutting the instrument or its vacuum system off.

Depicted in FIG. 7 is an ionization source which incorporates the multiple part capillary of the invention where the ion production means is an ESI sprayer device, shown as spray needle 36 in spray chamber 40. During normal operation of a preferred embodiment with an ESI source, sample solution is formed into droplets at atmospheric pressure by spraying the sample solution from spray needle 36 into spray chamber 40. The

spray is induced by the application of a high potential between spray needle 36 and entrance 26 of first capillary section 28 within spray chamber 40. Sample droplets from the spray evaporate while in spray chamber 40 thereby leaving behind an ionized sample material (i.e., sample ions). These sample ions are accelerated toward capillary inlet 26 of channel 27 by an electric field generated between spray needle 36 and inlet 26 of first section 28 of capillary 35. These ions are transported through first channel 27 into and through second channel 32 to capillary outlet 34. As described above with regard to FIG. 4, first section 28 is joined to second section 33 in a sealed manner by union 29. The flow of gas created by the pressure differential between spray chamber 40 and first transfer region 45 further causes the ions to flow through the capillary channels from the ionization source toward the mass analyzer.

Still referring to FIG. 7, first transfer region 45 is formed by mounting flange 48 on source block 54 where a vacuum tight seal is formed between flange 48 and source block 54 by o-ring 58. Capillary 35 penetrates through a hole in flange 48 where another vacuum tight seal is maintained (i.e., between flange 48 and capillary 35) by o-ring 56. A vacuum is then generated and maintained in first transfer 45 by a pump (e.g., a roughing pump, etc., not shown). The inner diameter and length of capillary 35 and the pumping speed of the pump are selected to provide as high a rate of gas flow through capillary 35 as

reasonably possible while maintaining a pressure of 1 mbar in the first transfer region 45. A higher gas flow rate through capillary 35 will result in more efficient transport of ions.

Next, as further shown in FIG. 7, first skimmer 51 is placed adjacent to capillary exit 34 within first transfer region 45. An electric potential between capillary outlet end 34 and first skimmer 51 accelerates the sample ions toward first skimmer 51. A fraction of the sample ions then pass through an opening in first skimmer 51 and into second pumping region 43 where pre-hexapole 49 is positioned to guide the sample ions from the first skimmer 51 to second skimmer 52. Second pumping region 43 is pumped to a lower pressure than first transfer region 45 by pump 53. Again, a fraction of the sample ions pass through an opening in second skimmer 52 and into third pumping region 44, which is pumped to a lower pressure than second pumping region 43 via pump 53.

Once in third pumping region 44, the sample ions are guided from second skimmer 52 to exit electrodes 55 by hexapole 50. While in hexapole 50 ions undergo collisions with a gas (i.e., a collisional gas) and are thereby cooled to thermal velocities. The ions then reach exit electrodes and are accelerated from the ionization source into the mass analyzer for subsequent analysis.

Another application of the present invention is to provide a simple and efficient method and apparatus for integrating two source assemblies. As depicted in FIG. 8, a complete ion source

may include a multitude of sub-assemblies. For example, ion source 80 includes ion production means sub-assembly 81 and vacuum sub-assembly 82. The ion production means sub-assembly 81 includes, among other things, spray chamber 40 and spray needle 36. The vacuum sub-assembly 82 includes among other things, pump 53 and ion optical elements 49-52 and 55 having pumping restrictions at elements 51 and 52 for guiding ions into the mass analyzer. In prior art sources and instruments, the capillary would be integrated entirely in one sub-assembly -- e.g., the vacuum sub-assembly 82. As a result, significant effort is required in prior art systems to align the ion production means sub-assembly 81 (specifically the spray needle) with the vacuum sub-assembly 82 (specifically the capillary entrance). The multiple part capillary according to the present invention can be used to ease the integration of such sub-assemblies by including capillary sections in each of the sub-assembly.

In the embodiment of FIG. 8, capillary section 28 is an integral component of ion production means sub-assembly 81 and capillary section 33 is an integral component of vacuum sub-assembly 82. Sub-assemblies 81 and 82 are integrated in part by joining capillary sections 28 and 33 together via union 29. Any necessary alignments are performed within a given sub-assembly (e.g., alignment of spray needle 36 with entrance 26 of channel 27). In alternate embodiments, any variety of sub-assemblies might be integrated, in part or in whole, by including capillary sections

in these sub-assemblies and subsequently joining these capillary sections together as discussed with respect to FIG. 8. Further, any number of sub-assemblies with any variety of functions might be used. Such functions might include ion production, desolvation of spray droplets via a heated capillary section, ion transfer to the mass analyzer, etc. Clearly, any type of atmospheric pressure ionization means, including ESI, API MALDI, atmospheric pressure chemical ionization, nano electrospray, pneumatic assist electrospray, etc., could be assembled into a source in this way.

The capillary according to the present invention might also be used to transport ions from ionization means remote from the mass spectrometer instrument. This is exemplified by the embodiment shown in FIG. 9. Depicted in FIG. 9 is an embodiment of the multiple part capillary according to the invention as used for integrating a sample preparation robot with an Atmospheric Pressure Ionization (API) source. Specifically, the system shown comprises, among other things: robot 90; robot arm 91; sample tray (not shown); source tray 92; sprayer 93; multiple part capillary 98 comprising first section 28 having inlet 26, second section 33 having outlet 34, and union 29; gas transport line 94; source cover 95; vacuum sub-assembly 96; and mass analyzer 97.

Robots such as in the embodiment of FIG. 9 -- for example, a Gilson 215 Liquid Handler Robot -- consist of a robot arm 91, which may be used to manipulate samples, "trays" of samples, sample containers, etc. Robot arm 91 may be used to move

samples, solutions, and reactants from one container (i.e., tubes, vials, or microtiter wells, etc.) to another. By mixing analyte(s), solvent(s), and reactant(s) in a predefined way, the robot may be used to prepare samples for subsequent analysis.

As depicted in FIG. 9, sample spray and ionization occurs within robot 90 and only ions would be transported -- via multiple part capillary 98 -- to mass analyzer 97. In the particular embodiment shown, a specially prepared source tray 92 is used. Sample is obtained by robot 90 from a sample tray by sucking solution into sprayer 93. Robot arm 91 using positioning means then moves sprayer 93 from source tray 92 to a predefined location near entrance 26 of capillary 98. Drying gas can be transported into source tray from vacuum sub-assembly 96 via a gas transport line 94. The drying gas may be used to assist the evaporation of the droplets and passage of ions into capillary 98. Sprayer 93 is attached to robot arm 91 and set at ground potential (of course, any ESI sprayer may be used (e.g., pneumatically assisted sprayers with or without pneumatic spray lines, nanosprayer needles, high voltage sprayers, etc.)), while inlet 26 to first section 28 of capillary 98 is set at a high voltage via contact through union 29 and end cap 30A to a power supply (not shown). This potential difference between sprayer 94 and first section 28 (in addition to pneumatic gas (if using a pneumatic sprayer)) then induces the spray of the sample solution and the production of analyte ions.

Once the ions enter inlet 26 of capillary 98 they are carried with a drying gas into the vacuum system of the mass spectrometer. This may comprise a plurality vacuum chambers 95, 96, 97 connected to differential pumps. Additionally, any number of ion optical devices (i.e., electrostatic lenses, conventional ion guides, etc.) may be used within the vacuum system to aid in the transport of the ions to the mass analyzer. Once in the mass analyzer, the sample ions are analyzed to produce a mass spectrum. Some of the analyzers which may be used in such a system include quadrupole, ICR, TOF, etc.

The capillary according to the present invention is also useful in transporting ions from varying locations during operation. Turning next to FIG. 10, shown is an embodiment of the multiple part capillary according to the invention as a means for integrating a sample preparation robot with an elevated pressure MALDI source for use in mass spectrometry. The system depicted in FIG. 10 comprises a laser 99, attenuator 100, fiber optic 101, robot 90 having robot arm 91 for control and movement of sample probe 102, MALDI sample tray 103, sample holder 104, alternative embodiment of capillary 98 having first section 105, second section 33 joined by union 29, ionization source cover 95, vacuum sub-assembly 96, and mass analyzer 97.

The alternative embodiment of the multiple part capillary of the invention as shown in FIG. 10 comprises a flexible first section 105 such that its inlet end may be moved by robot arm 91

to various positions for acceptance of the MALDI samples to be analyzed. As implied by FIG. 10, sample preparation and ionization may both be performed by robot 90 such that only ions would be transported through the multiple part capillary 98 to vacuum sub-assembly 96 and ultimately to mass analyzer 97. Specifically, robot arm has attached to its end sample probe 102, and fiber optic 101 for directing the laser beam from laser 99 onto sample holder 104 to ionize samples thereon. Alternatively, mirrors may be used to re-direct the laser beam from laser 99 onto sample holder 104 to ionize samples thereon. Yet another alternative includes mounting laser 99 onto robot arm 91 or some other robot arm, which would be able to direct the laser beam onto the sample. This embodiment also allows for laser 99 to be easily moved from one location to another with precision. The ions formed by the laser beam hitting the samples on sample holder 104 are then carried by the gas flow into and through capillary 98 to the differential pumping region of vacuum sub-assembly 96, where additional ion optics (not shown) are designed to further transport the ions from outlet end of capillary 98 to mass analyzer 97 for subsequent analysis. Any known ion optics may be used, including but not limited to, electrostatic electrodes, RF electrodes, optics of the type referred to in Franzen et al. U.S. Patent No. 5,663,561 or Whitehouse et al. U.S. Patent No. 5,652,427, etc.

As shown in FIG. 11, which depicts an embodiment of the

multiple part capillary for use with a MALDI probe, the multiple part capillary according to the invention provides a means for integrating a sample preparation robot with MALDI mass analysis. Shown in FIG. 11 are capillary 105, robot arm 91, receptacle 106, fiber optic 101, and sample plate 104 with raised conical formations 107 onto which samples (not shown) are deposited. Sample plate 104 and the conical formations form a unitary device composed of conducting material (e.g., stainless steel). In this alternate embodiment, capillary section 105 optionally comprises a specially shaped orifice which fits over cone-shaped sample holder formations 107 (one at a time) in such a way that gas flowing through capillary 98 readily captures the ions formed from the sample by laser desorption ionization. Therefore, the sample is desorbed directly into the gas flow, thereby resulting in a minimal loss of ions (i.e., for an efficient transfer of ions). Alternatively, chemical ionization may be performed in the capillary or in the vacuum for such efficient transfer of ions. Optionally, a potential may be applied between sample carrier 104 and capillary 78 section 105 to help draw ions into the channel of capillary 78 section 105. Also, fiber optic 101 might be adjusted via piezo electrics or other mechanics to direct the laser beam to any region of the specific cone-shaped sample of samples 107 to be ionized. Optionally, this redirecting of the laser beam may occur during the ionization process such that ultimately the entire sample is ionized. It is

noted that several laser "shots" may be needed to desorb the entire sample.

While the present invention has been described with reference to one or more preferred embodiments, such embodiments are merely exemplary and are not intended to be limiting or represent an exhaustive enumeration of all aspects of the invention. The scope of the invention, therefore, shall be defined solely by the following claims. Further, it will be apparent to those of skill in the art that numerous changes may be made in such details without departing from the spirit and the principles of the invention. It should be appreciated that the present invention is capable of being embodied in other forms without departing from its essential characteristics.